## Middle and late Holocene climate change and human impact inferred from diatoms, algae and aquatic macrophyte pollen in sediments from Lake Montcortès (NE Iberian Peninsula)

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ORIGINAL PAPER

# Middle and late Holocene climate change and human impact inferred from diatoms, algae and aquatic macrophyte pollen in sediments from Lake Montcortès (NE Iberian Peninsula)

**Paolo Scussolini · Teresa Vegas-Vilarrúbia · Valentí Rull · Juan Pablo Corella · Blas Valero-Garcés · Joan Gomà**

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**Abstract** During the middle and late Holocene, the Iberian Peninsula underwent large climatic and hydrologic changes, but the temporal resolution and regional distribution of available palaeoenvironmental records is still insufficient for a comprehensive assessment of the regional variability. The high sedimentation rate in karstic, meromictic Montcortès Lake (Catalan pre-Pyrenees) allows for a detailed reconstruction of the regional palaeoecology over the last 5,340 years using diatom analysis, aquatic pollen, sedimentological data, and historic documentary records. Results show marked fluctuations in diatom species assemblage composition, mainly between dominant *Cyclotella* taxa and small Fragilariales. We suggest that the conspicuous alternation between *Cyclotella comta* and *C. cyclopuncta* reflects changes in trophic state, while the succession of centric and pennate species most likely reflects changes in the hydrology of the lake. The diatom assemblages were used to identify six main phases: (1) high productivity and likely lower lake levels before 2350 BC, (2) lower lake levels and a strong arid phase between 2350 and 1850 BC, (3) lake level increase between 1850 and 850 BC, (4) relatively high lake level with fluctuating conditions during the Iberian and Roman Epochs (650 BC–350 AD), (5) lower lake levels, unfavourable conditions for diatom preservation, eutrophication and erosion triggered by increased human activities in the watershed during the Medieval Climate Anomaly (900–1300 AD), and (6) relatively higher lake levels during the LIA (1380–1850 AD) and afterwards. The combined study of diatoms, algae and pollen provides a detailed reconstruction of past climate, which refines understanding of regional environmental variability and interactions between climate and socio-economic conditions in the Pyrenees.

**Keywords** Diatoms · Meromixis · Multi-proxy · Palaeoenvironmental reconstruction · Pollen · Pyrenees

P. Scussolini · T. Vegas-Vilarrúbia (✉) · J. Gomà
Faculty of Biology, Department of Ecology, Universitat de Barcelona, Barcelona, Spain
e-mail: tvegas@ub.edu

P. Scussolini
Faculty of Earth and Life Sciences, Department of Marine Biogeology, Vrije Universiteit, Amsterdam, The Netherlands

V. Rull
Institut Botànic de Barcelona (CSIC-ICUB), Barcelona, Spain

J. P. Corella · B. Valero-Garcés
Instituto Pirenaico de Ecología (CSIC-IPE), Zaragoza, Spain

## Introduction

With greater awareness of modern global change, there is growing interest in predicting how, to what

extent and at what rate ecosystems will change. Freshwater primary producers can be very sensitive to climate change, especially to abrupt fluctuations that alter their habitats and metabolism. Diatom response to Holocene climatic variability has been documented across many latitudes, owing to their direct (Wolfe 2003) and indirect responses to climate change (Finkelstein and Gajewski 2007; Morellón et al. 2009a). Diatom community diversity and productivity respond quickly to changes in conductivity, nutrient concentration, and habitat availability that are associated with variations in the hydrologic balance (precipitation/evaporation) of lakes. Thus, diatoms are sensitive recorders of climatic fluctuations. Similarly, changes in littoral macrophyte communities, reflected in their pollen record, record variations in both water levels and nutrient status of lakes (Battarbee et al. 2001).

Mediterranean areas, such as most of the Iberian Peninsula (IP), display negative annual water balance and have a long history of human occupation. Most palaeoenvironmental records from the IP indicate a transition from drier climate in the middle Holocene to a more humid late Holocene (Cacho et al. 2010). Studies of the last three millennia show a variable global climatic pattern, over secular and decadal scales (Mann and Jones 2003; Valero-Garcés et al. 2006). Among the phases of climate change, the most pertinent to the IP system are the Iberian Roman Humid Period (IRHP) (650 BC–350 AD) (Martín-Puertas et al. 2009), the Medieval Climate Anomaly (MCA) (900–1300 AD) and the Little Ice Age (LIA) (1300–1850 AD) (Mann et al. 2009). The IRHP includes the most humid interval of the last 4,000 years in southern Spain (Martín-Puertas et al. 2008). The MCA was relatively warm and arid (Morellón et al. 2009a; Martín-Puertas et al. 2008), while the LIA brought colder and generally wetter, although fluctuating climate conditions (Pla and Catalan 2005; Chueca Cía et al. 2005). Recent reviews of climate in the IP (Cacho et al. 2010) show large variability during recent centuries: (1) increased temperature and precipitation during the fourteenth century (Saz 2003), (2) an increase in drought events in the northeastern IP after 1600 AD (Vicente-Serrano and Cuadrat 2007), (3) an increase in extreme events during the LIA (Barriendos and Martín-Vide 1998), and (4) humidity increase over the Mediterranean coast near the end of the sixteenth and eighteenth centuries and during the second half of the nineteenth century.

Lake Montcortès, a karstic meromictic lake in the Pre-Pyrenean Range of NE Spain has a high sedimetation rate and a robust chronological model for the last 6,000 years. It was selected for detailed palaeoenvironmental study using biological proxies because previous sedimentological (Corella et al. 2010), limnological (Camps et al. 1976; Modamio et al. 1988), palynological (Rull et al. 2010) and historical (Marugan and Oliver 2005; Bosch and Santacana 2009; Còts 2005) analyses of Lake Montcortès indicated evidence of distinct environmental changes due to climate and human impact during middle and late Holocene. Meromictic lakes are known to be very sensitive to environmental changes (Hakala 2004). In this study we used diatoms, other algae remains and pollen from aquatic higher plants to infer past environmental changes, and we compared our results to previous regional reconstructions. Our data show rapid changes in the limnology and hydrology of the lake during the middle to late Holocene, coherent with regional and local climate reconstructions.

## Study site

Lake Montcortès (42°19′ N, 0°59′ E, 1,027 m altitude) is a karstic lake situated on the southern slopes of the Central Pyrenees, in the Pallars region of Catalonia (Fig. 1). The bedrock of the lake catchment is mainly Triassic carbonates, claystones and evaporites (Rosell 1994). The basin has a sub-circular shape with very steep slopes and a surface area of 17 ha. The diameter is roughly 500 m and the maximum depth is 29 m. The lake catchment is vegetated and features transitional elements between Mediterranean and Sub-Mediterranean forests, meadows, and hygrophile littoral vegetation around the lake. Land use today is limited to the cultivation of cereals and to livestock pastures, however, the area has a relatively long history of human occupation, with increasing population from the Neolithic to medieval times, a maximum in the nineteenth century, and continuous depopulation in the industrial and post-industrial periods (Rull et al. 2010). Drainage is mostly via groundwater and secondary ephemeral streams, which seasonally supply clastic sediments (Corella et al. 2010). An outlet on the north shore controls maximum water level.

Even though Lake Montcortès is considered meromictic (Camps et al. 1976), there is evidence that it was holomictic during the winter of 1978–1979 (Modamio et al. 1988). Measurements in August 2007, carried out by the Ebro Hydrographic Survey, showed an anoxic hypolimnion, alkaline water (pH = 8.4) and an oligotrophic state (total ammonia $< 0.05$ mg $l^{-1}$, nitrates = 0.788 mg $l^{-1}$, nitrites = 0.011 mg $l^{-1}$, total phosphorus $< 0.005$ mg $l^{-1}$). The phytoplankton community is dominated by *Oscillatoria rubescens* and *Cyclotella comta* (Camps et al. 1976; Modamio et al. 1988).

## Materials and methods

Two Kullenberg cores (MON04-1A-1K and MON04-4A-1K) were retrieved from the deepest part of the basin to constitute a composite sediment section (Fig. 1). A short gravity core was taken (MON07-1A-1U) to obtain the sediment/water interface. In addition, two surface sediment samples were taken at maximum depth and near the littoral zone, for use as modern representatives from the two areas.

Cores were sub-sampled every 2 cm for Total Organic Carbon (TOC), Total Inorganic Carbon (TIC) and Total Nitrogen (TN). TOC and TIC were measured in a LECO SC144 DR furnace, and TN by a VARIO MAX CN elemental analyzer. Sedimentological and geochemical characteristics of the composite sediment sequence were described by Corella et al. (2010). Total phosphorus (TP) in the sediment was analyzed in core MON04-1A-1K by X-Ray Fluorescence (XRF) using an ITRAX XRF core scanner from the Large Lakes Observatory (University of Minnesota, Duluth) with 20 mA current, 30 s count time and 30 kV voltage at 1 mm resolution. TP content was expressed as element intensities in counts per second (cps).

For diatom analysis, 52 subsamples were collected at 10-cm intervals along the composite sediment record. Diatoms were extracted from 0.1 g of dry sediment and prepared using the method described by Abrantes et al. (2005). They were mounted in Naphrax © and analyzed with a Polyvar light microscope at 1,000× magnification. A minimum of 300 valves was counted for each sample whenever possible. Relative abundance of diatom species is given in percentages and valve influx was calculated

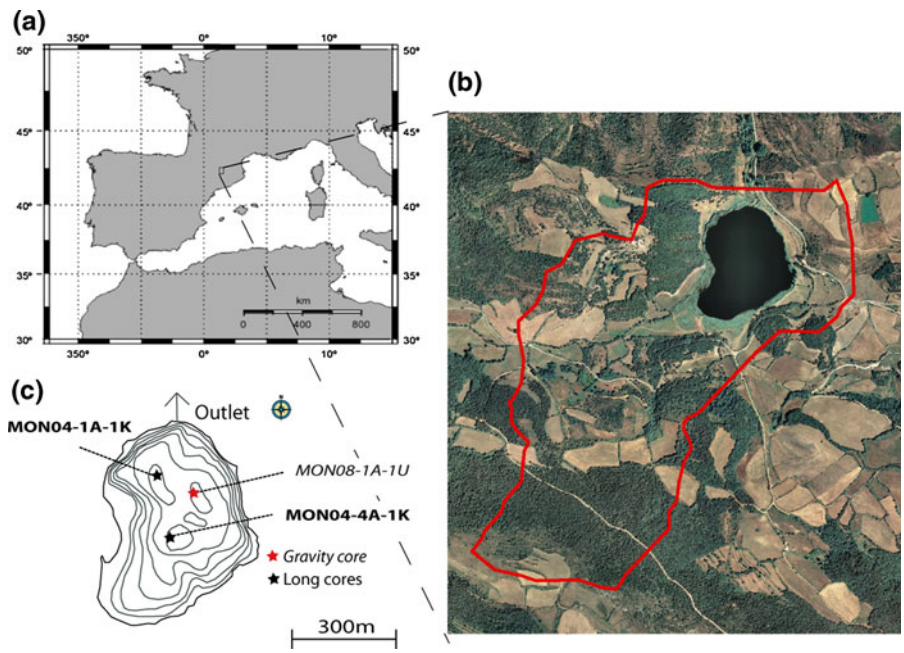


**Fig. 1** Location of Montcortès Lake. **a** Geographical location within the Iberian Peninsula. **b** Aerial photograph of the area surrounding Montcortès Lake. *Red line* indicates the lake's catchment area. **c** Bathymetric map of Montcortès Lake and locations of the three studied Kullenberg cores

using microspheres (Battarbee et al. 2001). Taxonomic identifications were made using several references (Krammer 1997; Krammer and Lange-Bertalot 1986–2004; Lange-Bertalot 1980). Centric to pennate diatom ratio (C/P) was calculated and used as an indicator of the relative abundance of planktonic to benthic habitat availability, although it is also known to reflect changes in trophic status (Cooper 1995). The decrease in diatom preservation was expressed by the percentage of diatom valves showing dissolution and/or breakage (dissolution index). Both indicate the impact of diagenesis as well as the importance of silicification for diatom preservation (Flower 1993; Ryves et al. 2001). Sometimes differential preservation among species might not properly reflect the diagenetic features of the sediment (Reed et al. 2010). In our case, the central areas of most *Cyclotella* taxa remained intact, so they were easily identified, and hence did not interfere with counting accuracy. Fragilariales are commonly well preserved, while other taxa show variable preservation, however the most abundant taxa could be identified reliably. Samples of $\sim$ 3-5 g of wet sediment were collected every 10 cm for pollen and algal remains. They were processed with standard palynological methods, including NaOH, HCl and HF digestions and density gradient centrifugation, without acetolysis (Bennett and Willis 2001). Two *Lycopodium* tablets (batch # 483,216; 18,583 spores/tablet) were added to each sample before chemical treatment. Residues were suspended in glycerine and slides were mounted with glycerine jelly. For more details, see Rull et al. (2010).

Diatom diagrams were plotted with *Psimpoll* and divided into biozones using the Optimal Splitting by Information Content Method (Bennett 1996). The identified diatom zones were applied to the palynological and geochemical data. Only taxa showing abundances >3% were illustrated. We related the diatom assemblages to the lake nutrient status using TP, TIC, TN and TOC content as indicators of trophic state. To better elucidate this relationship, we applied a constrained ordination method. To decide whether to use a linear or a unimodal method, the gradient length was measured using a detrended canonical correspondence analysis (DCCA), detrending-by-segments and non-linear re-scaling of axes. Because the gradient length of the first DCCA axis yielded a result of 3.18 standard deviation units, a linear model was chosen (Lepš and Šmilauer 2003). The selected redundancy analysis (RDA) was performed with CANOCO (ter Braak and Šmilauer 2002).

The chronology was developed using 11 radiocarbon dates on terrestrial plant remains (Corella et al. 2010). Calibrated BC/AD ages are used for discussion. The composite core sequence (538 cm) spans the last 5,340 years. Varve counts yielded a more accurate chronology for the last 1,500 years. Sedimentation rate between 538 cm (3390 BC) and 400 cm (124 AD) was about 0.04 cm year$^{-1}$, resulting in a diatom sample resolution of $316 \pm 80$ years. Between 400 cm and the top of the sequence, sedimentation rate increased to 0.26 cm year$^{-1}$, yielding a diatom sampling resolution of $36 \pm 18$ years.

## Results

### Diatom stratigraphy

According to the changes in diatom assemblage composition, five diatom zones were differentiated. Valve influx rates display large fluctuations. Between 356 cm and 124 cm, and in three other samples (538, 43, and 13 cm), diatoms are either too scarce for accurate counting or are lacking completely (Fig. 2). The most striking pattern throughout the record is that *Cyclotella comta* and *Cyclotella cyclopuncta* vary inversely, and only appear together at a single depth in zone III (Fig. 2). *Botryococcus* is always present, while pronounced and isolated peaks of *Tetraedron* occur at 310 cm and between 178 and 168 cm (Fig. 5). Cyperaceae pollen dominates the aquatic pollen throughout the entire record, except for the uppermost levels, where *Typha* is dominant or co-dominant (Fig. 4).

#### *Diatom zone I: 538–483 cm*

In this zone, centric diatoms (*Cyclotella* taxa) dominate and influx varies between $8.02 \times 10^4$ and $3.97 \times 10^6$ valves cm$^{-2}$ year$^{-1}$ (Fig. 2), while the dissolution index varies between 39 and 85%. *C. comta* displays three peaks. Its first minimum (518 cm) coincides with high abundances of *Pseudostaurosira brevistriata, Staurosirella pinnata, Fragilaria tenera* and *Eunotia meisteri*. After the third peak of *C. comta*, it is replaced by

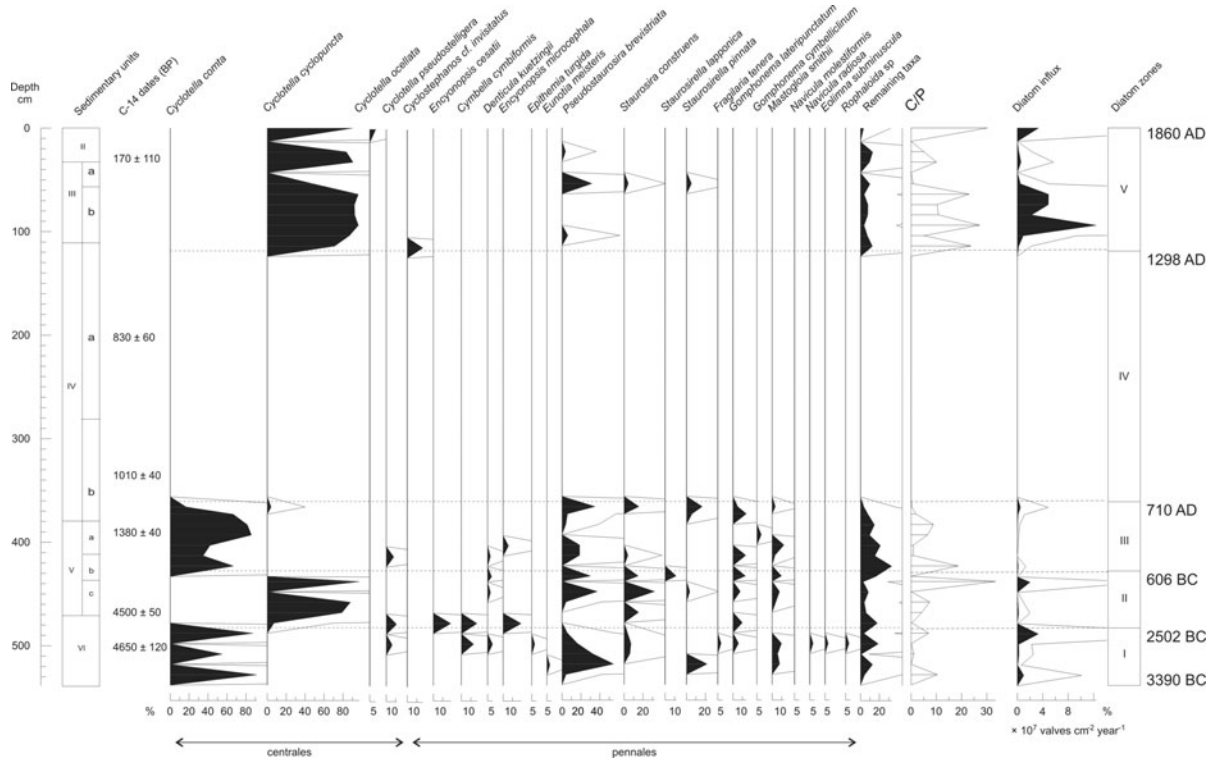


**Fig. 2** Relative abundance (%) of diatom taxa throughout the record. The *dotted lines* separate diatom zones V–I. Valve influx (valves $cm^{-2}$ $year^{-1}$) and centric: pennate ratio (C/P) variations in the record (538–0 cm). Sedimentary units are described in Corella et al. (2010). Radiocarbon ($^{14}C$) dates in calibrated years before present (BP)

*C. cyclopuncta,* and the C/P ratio increases to 1.0 (Fig. 2). This zone coincides with lithostratigrapic unit VI (532–470 cm) (Corella et al. 2010), composed of laminated facies with poor calcite preservation, and characterized by an upcore, decreasing trend in organic carbon and clay mineral content. TP in the sediment increases from the bottom to the middle of the zone, and decreases again towards the top. TN and TOC are the highest of the record, whereas TIC values are the lowest (Fig. 3).

*Diatom zone II: 483–428 cm*

In this zone, valve influx ranges from $9.87 \times 10^4$ to $2.00 \times 10^7$ valves $cm^{-2}$ $year^{-1}$, and centric taxa still dominate the diatom flora. *C. cyclopuncta* becomes the most important centric diatom in the lowest part, at the expense of *C. comta*. At 483 cm the accumulation rate reaches its highest value in the core, concurrent with an abundance of *C. cyclopuncta* > 97%. Near the top of the zone, *C. cyclopuncta* disappears, while Fragilariales and other pennate genera re-appear. Coinciding with peaks in the valve influx, C/P ratio values range above 1. The C/P values show distinct fluctuations and pennate diatoms peak at 448 cm. Dissolution index varies between 28 and 92%. This zone coincides with the lower part of lithostratigraphic unit V (subunit Vc: 470–430 cm), which is defined by the onset of biogenic varves composed of triplets of calcite, organic and detrital layers (Corella et al. 2010). The TP values are below the detection limit except in the lowest part of the zone. TOC and TN values are lower than in the previous zone, and TIC and TN show an increasing trend toward the top of the zone (Fig. 3).

*Diatom zone III: 428–361 cm*

The beginning of the zone is marked by the return of *C. comta* (67%), which becomes dominant. Valve influx is lower and less variable ($1.07 \times 10^4 - 4.84 \times 10^6$ valves $cm^{-2}$ $year^{-1}$) than in the previous zone.

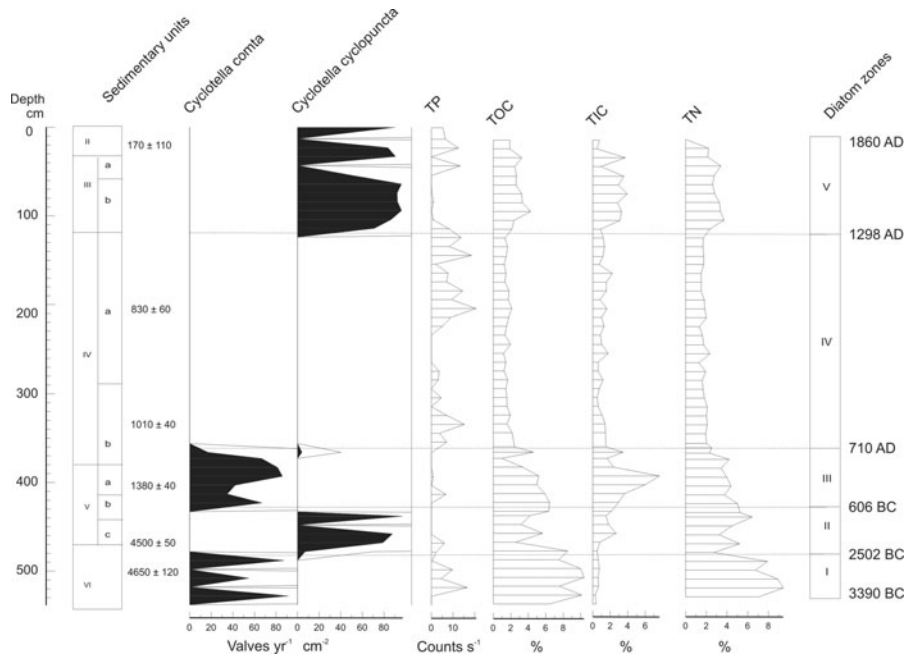


**Fig. 3** Relationship between the relative abundances of *C. comta* and *C. cyclopuncta* and concentrations of total phosphorus (TP), total nitrogen (TN) and total organic carbon (TOC) in the sediment. *Dotted lines* separate diatom zones V–I. Radiocarbon ($^{14}$C) dates in calibrated years before present (BP)

At 413 cm, the influx and C/P values decrease. The percentage of *C. comta* diminishes, but this species is still the best represented. Because several pennate taxa (*P. brevistriata*, *Gomphonema lateripunctatum*) gain in importance, the C/P ratio is close to 1. Between 400 and 390 cm, *C. comta* recovers, resulting again in a higher C/P ratio. At the upper part of this zone, *C. comta* diminishes abruptly, and in the same sample *C. cyclopuncta* also occurs. This is the only case in the whole record where the two dominant species of *Cyclotella* coexist. The C/P value reveals the renewed importance of pennate diatoms. The dissolution index varies between 29 and 94% and reaches its maximum value at 383 cm, coinciding with the peak of *C. comta.* This may explain why valve influx is lower here than in the following pennate-rich phase. At the transition between zones III and II, the valve influx decreases abruptly. This zone coincides with the middle and upper part of lithostratigraphic unit V (432–377 cm) and the lowermost part of clastic unit IV (Corella et al. 2010). Calcite layers are less frequent in organic-rich subunit Vb (432–405 cm), but they predominate in the upper part (subunit Va, 405–377 cm), which is characterized by the highest TIC values in the sediment sequence. TP was only detected in subunit Vb. TOC and TN show decreasing values. The upper part of this zone coincides with marked decreases in TN, TIC and TOC.

*Diatom zone IV: 361–119 cm*

This zone is almost devoid of diatoms. Diatoms were completely lacking in the interval between 186 and 176 cm and it corresponds to a thick detrital layer, probably deposited during a storm-related event (Corella et al. 2010).

This zone is dominated by Cyperaceae pollen (80–90%). All the other types are scarce and display highly variable values (Fig. 4). *Typha/Sparganium* is discontinuous, but present throughout the zone, while the other pollen types are represented by localized and isolated peaks, except for *Cladium*-t, which is more continuously present above 280 cm. *Utricularia* is restricted to the middle of the zone, and *Potamogeton* and *Ranunculus* occur only in the upper part.

The most abundant algal remains (Fig. 5) are *Botryococcus,* but the relative concentration curve is characterized by several pronounced peaks of *Pseudoschizaea* and *Tetraedron*, which reach values of 70–90%. *Spirogyra* shows scattered, but continuous peaks, while *Pediastrum* and *Zygnema* show a similar pattern, but disappear around 200 cm. *Cosmarium* and *Debarya* show single peaks.

This zone coincides with the clastic lithostratigraphic unit IV (377–109 cm), which displays abundant and thick (up to 15 cm) turbidite beds intercalated within biogenic varves (Corella et al. 2010), and has a high sedimentation rate (0.45 cm year$^{-1}$). TIC, TOC and TN values remain relatively low and stable throughout the unit, whereas TP increases abruptly, shortly after the onset of this unit, likely related to the higher sediment input from the catchment.

*Diatom zone V: 119–0 cm*

In this zone diatoms are again well represented. Two samples (43 and 13 cm), however, show no diatoms and coincide with detrital layers (Corella et al. 2010). Besides these two samples, valve influx in this zone is highest (from 2.18 $\times$ 10$^6$ valves cm$^{-2}$ year$^{-1}$ at 114 cm to 1.24 $\times$ 10$^8$ valves cm$^{-2}$ year$^{-1}$ at 94 cm) in the lower half of the zone. This is followed by a large decrease and subsequent recovery in the most recent sample (3.37 $\times$ 10$^7$ valves cm$^{-2}$ year$^{-1}$). *C. cyclopuncta* dominates with relative abundances >80%. Another centric diatom, *Cyclostephanos invisitatus* only occurs at 114 cm and it is followed by a short peak of *P. brevistriata*. *C. cyclopuncta* reaches its highest percentages between 94 and 64 cm, and then decreases until 43 cm, where it almost disappears. Along with the decline in *C. cyclopuncta*, minor peaks of Fragilariales occur. Between 43 and 23 cm, the diatom community is well represented again and *C. cyclopuncta* dominates until the present. *P. brevistriata* peaks briefly at 23 cm. At the top of this zone, i.e. in surface sediment, *C. cyclopunta* dominates overwhelmingly. With the exception of the samples at 43 cm and 13 cm, dissolution index values remain relatively low (23–56%).

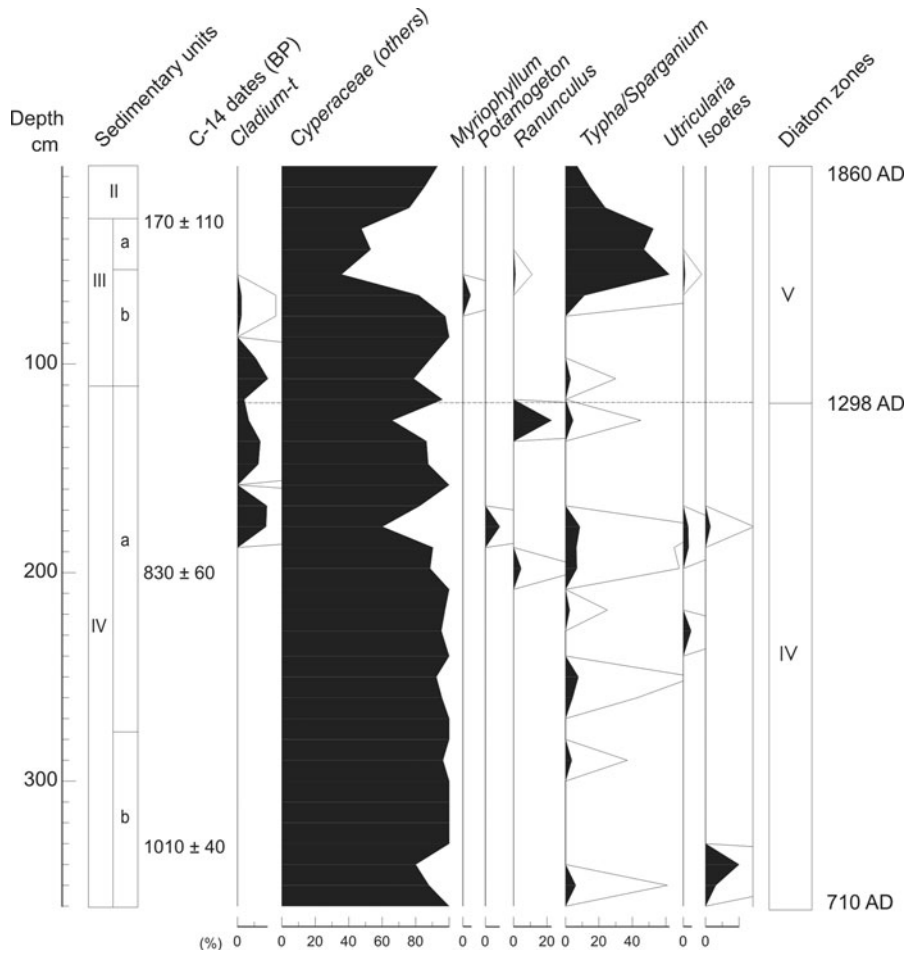


**Fig. 4** Relative abundance (%) of macrophyte taxa in the sediment sequence. *Dotted lines* separate diatom zones V–I. Radiocarbon ($^{14}$C) dates in calibrated years before present (BP)

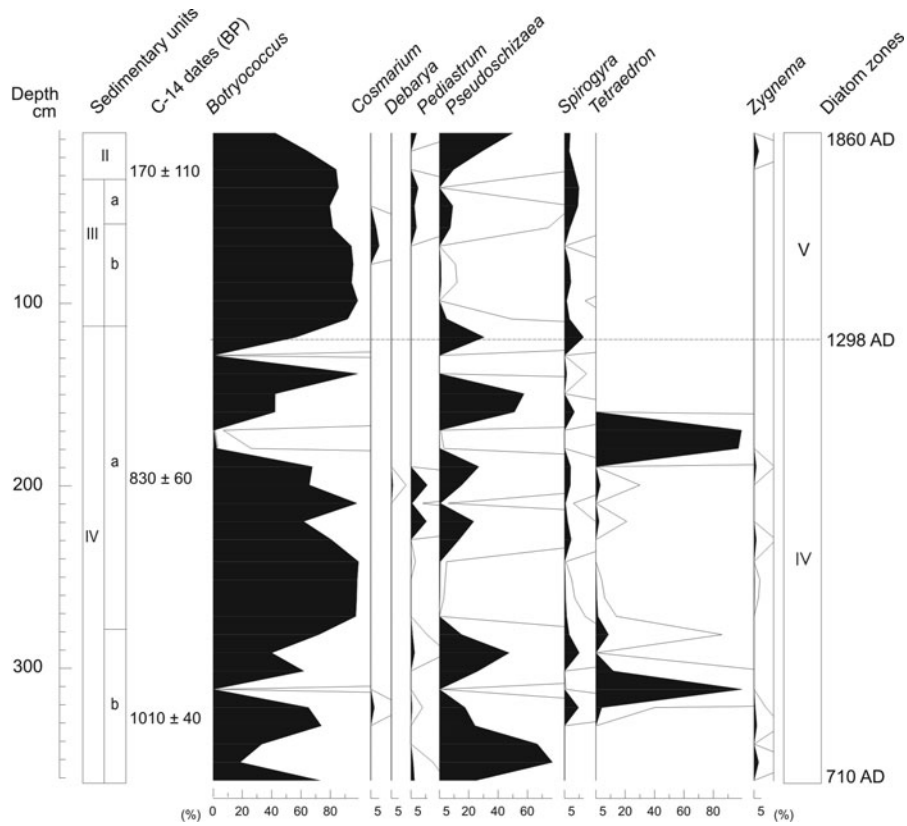


**Fig. 5** Relative abundance (%) of algae taxa in the sediment sequence. *Dotted lines* separate diatom zones V–I. Radiocarbon ($^{14}C$) dates in calibrated years before present (BP)

This zone is dominated by Cyperaceae in the lower (~90%) and top (80–90%) parts, whereas in the middle, *Typha/Sparganium* (~60%) are more frequent. Cyperaceae cover (80–90%) in the uppermost samples. *Cladium*-t decreases and disappears around 60 cm. *Ranunculus, Utricularia* and *Myriophyllum* are represented by single peaks around the middle of the zone, while *Potamogeton* is absent. *Botryococcus* is the dominant algae remnant (80–90%) throughout the zone, except at the top, where *Botryococcus* and *Pseudoschizaea* (~50% each) are more frequent. *Cosmarium* and *Zygnema* show isolated peaks at the middle and the top of the zone, respectively. The appearance of *Pediastrum* between 60 and 70 cm coincides with the increase and further dominance of *Typha/Sparganium*. *Tetraedron* and *Debarya*, present in zone IV, are absent here.

The TN, TIC and TOC values increase in zone V, while sediment TP declines noticeably (Fig. 3), displaying strongly oscillating values in the lower part and top of the zone, and becoming negligible from 64 to 43 cm.

The zone coincides with lithostratigraphic units III (109-31 cm) and II (31-0 cm). Unit III is characterized by the presence of biogenic varves with low detrital input, whereas during clastic unit II, the varves incorporate thick detrital layers (Corella et al. 2010). The clastic unit II displays high TP related to the detrital layers, in contrast with biogenic unit III, which shows higher TOC and TIC.

## Redundance analysis (RDA)

To analyze the alternating presence of the two *Cyclotella* species, we ran a RDA, considering TOC, TN and TP accumulations in sediment as indicators of nutrient enrichment. The two first axes account for 21.4% of the total variance. Axis 1 accounts for 15.3% of the variance and is positively correlated with TN and TIC (Fig. 6). The second axis explains 6.1% of the variance and is positively correlated with TP and TOC. *C. cyclopuncta* and *C. comta* show totally opposite ordination along axis 1. This suggests that these diatoms are more related to TN and TIC than to TP and TOC in sediments,

though *C. compta* is more related to TP and TOC than *C. cyclopuncta*. Several pennate species, especially of the Fragilariales (*P. brevistriata and Staurosira construens*), as well as *G. lateripunctatum* and *Mastogloia smithii* are negatively correlated with the second axis, which involves an inverse relationship with sedimentary TP and TOC. The vectors corresponding to these taxa are virtually orthogonal to those of both *Cyclotella* species, suggesting a strong inverse relationship.

## Discussion

### 3390–2420 BC; 5340–4370 cal BP (Diatom zone I); Neolithic age

The dominance of *C. comta*, a species of the *Cyclotella radiosa* complex that is common in meso-eutrophic waters (Anneville et al. 2002; Krammer and Lange-Bertalot 2004; Wunsam et al. 1995), is interrupted by short episodes of decline, when Fragilariales become more important. Throughout the whole record, periods dominated by *C. comta* may indicate stability phases, with higher lake levels favouring plankton development. In contrast, coincidence of peaks in Fragilariales with peaks of the "remaining" taxa (Fig. 2) in the middle part of zone I probably reflects unstable, shallower phases (Smol and Cumming 2000), likely related to lake level fluctuations. This is coherent with the fact that small Fragilariales often are dominant in shallow lakes (Padisák and Dokulil 1994) and their presence corresponds to a period with some sedimentological evidence of persistent shallower deposition (higher organic matter, littoral fossil presence). Some diatoms of this group respond to higher conductivities, alkalinities and pH values (e.g. *P. brevistriata*, *S. pinnata, S. construens, M. smithii*) (Schmidt et al. 2004), and are classed as facultative planktonic taxa (Wilson et al. 2008). Additionally, the inverse relationship of *S. pinnata* and *S. construens* (RDA) with *C. comta*, TP and TOC suggests phases with lower sediment input and runoff, responsible for less TP influx from the catchment. Sedimentological evidence suggests dominance of relatively shallow environments with high productivity, high organic matter accumulation, anoxic conditions and calcite dissolution in the hypolimnion (Corella et al. 2010). Calcite dissolution is known to occur in Alpine meromictic lakes during periods with strong anoxic conditions and $CO_2$ supersaturation in the monimolimnion (Schmidt et al. 2004). The occurrence of gastropod shells and layers with reworked littoral carbonate material is coherent with more extensive littoral environments in Montcortès during this period, and generally lower lake levels. On the other hand, planktonic *C. comta* was also found as the dominant and sub-dominant type in shallow lakes in Hungary (e.g. Lake Balatón), with water depths between 1.5 m and 6 m (Padisák et al. 1990, 2003). Thus, both biological and sedimentological proxies point to fluctuating and relatively low lake levels, although even during shallow conditions, the lake was deep enough to maintain plankton. The presence of acidophilous species *Eunotia meisteri* and *Fragilaria tenera* suggests the possibility of lower pH episodes that could have been caused by the mixing of mixolimnion with the monimolimnion. Although *E. meisteri* and *F. tenera* may also be part of reworked material from the littoral zone (Schmidt et al. 2004), their occurrence is coherent with less alkaline conditions inferred for this period based on the high organic matter content of the sediments and evidence of dissolution of endogenic calcite (Corella et al. 2010). Small increases in acidification of the system may also have occurred.

Numerous studies have found evidence for drier climate in the IP during this period (Cacho et al. 2010) that correlate with similar changes in the Alps (Magny et al. 2008) and the end of the African Humid Period in northern Africa (deMenocal et al. 2000) (Table 1). This interval approximately corresponds to the Neolithic Age (4000–3000 BC) and the beginning of the Chalcolitic period ~3000 BC, when humans abandoned caves, and deforestation and nomadic life started at a regional scale. Archaelogical sites (Cista de Cartanis) exist close to Montcortès Lake (Còts 2005; Bosch and Santacana 2009) and indicate early forest clearance by fire (Còts 2005), hence some nutrient input to the lake is likely to have occurred during this period.

### 2420–605 BC; 4370–2555 cal BP (Diatom zone II); Chalcolithic Period and Bronze Age

Shortly after the beginning of this zone, the period between 2360 and 1900 BC is characterized by the

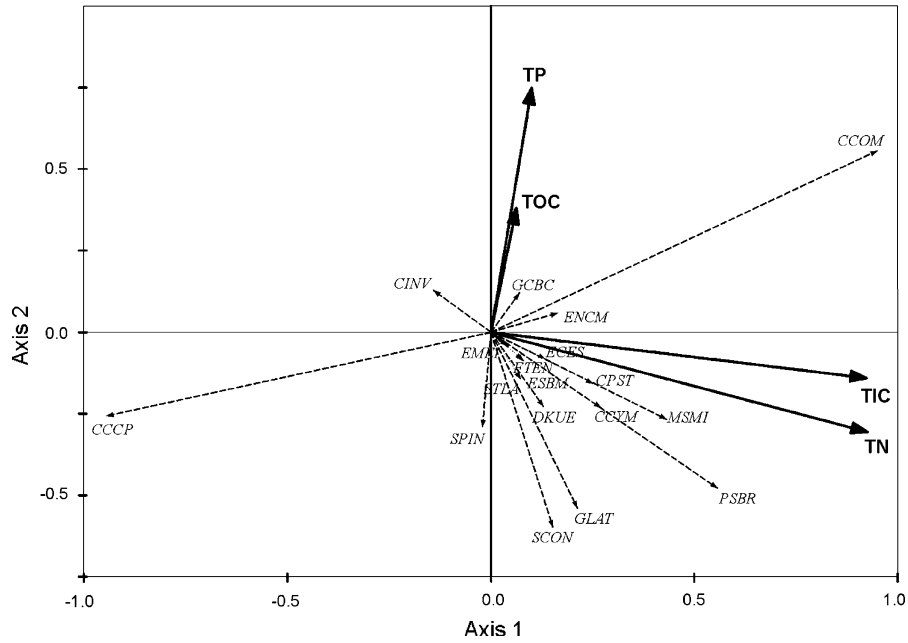


**Fig. 6** RDA plot representing the ordination of environmental variables and species on the first and second axes. *Vectors* indicate the direction and relative strength of the relationship between ordination axes scores and environmental variables and species abundance. For a better visualization, only species relevant to the results are represented. Codes are: *TOC* total organic carbon, *TP* total phosphorus, *TN* total nitrogen, *TIC* total inorganic carbon, *CCCP Cyclotella cyclopuncta* Hakansson and Carter, *CCOM Cyclotella comta* (Ehrenberg) Kützing, *CCYM Cymbella cymbiformis* Agardh, *CINV Cyclostephanos invisitatus* (Hohn and Hellerman) Theriot, Stoermer and Hakansson, *CPST Cyclotella pseudostelligera* Hustedt, *DKUE Denticula kuetzingii* Grunow, *EMEI Eunotia meisteri* Hustedt, *ENCM Encyonopsis microcephala* (Grunow) Krammer, *ECES Encyonopsis cesatii* (Rabenhorst) Krammer, *ESBM Eolimna subminuscula* (Manguin) Moser, Lange-Bertalot and Metzeltin, *FTEN Fragilaria tenera* (Smith) Lange-Bertalot, *GCBC Gomphonema cymbelliclinum* Reichardt and Lange-Bertalot, *GLAT Gomphonema lateripunctatum* (Reichardt and Lange-Bertalot), *PSBR Pseudostaurosira brevistriata*, (Grunow) Williams and Round, *SCON Staurosira construens* Ehrenberg, *SPIN Staurosirella pinnata* (Ehrenberg) Williams and Round, *STLA Staurosirella lapponica* (Grunow) Williams and Round, *MSMI Mastogloia smithii* Thwaites

disappearence of *C. comta* and the appearance of *C. cyclopuncta*, which prefers mesotrophic to oligotrophic conditions (Padisák et al. 2003; Tolotti et al. 2007; Wunsam et al. 1995). Although there is not a strong relationships beween sedimentary TP and *Cyclotella* abundances, as in the RDA, concurrent increases of *C. comta* and sedimentary TIC and TN, along with the opposite trend in *C. cyclopuncta*, suggest that these shifts might be associated with changes in productivity. This is in agreement with the findings of Wunsam et al. (1995) who reported TP optima of 16.6 μg $l^{-1}$ for *C. radiosa* type 1 and 12.3 μg $l^{-1}$ for *C.* aff. *cyclopuncta.* New pennate species appear, e.g. *S. construens, Encyonopsis cesatii* and *Cymbella cymbiformis* (Wilson et al. 2008; van Dam et al. 1994), pointing to the expansion of benthic and littoral habitats due to decreasing water levels, and probably to higher alkalinities and pH values (e.g. *S. pinnata, C. cymbiformis*). The deposition of more organic-rich, littoral facies (Unit VI) is also coherent with the inference for shallower conditions in the lake. Concurrent arid phases have been detected in the IP (Cacho et al. 2010), for instance in nearby lake Estanya (4800 and 4000 cal BP) (Morellón et al. 2009b), elsewhere in the Mediterranean basin (Harrison and Digerfeldt1993; Sadori et al. 2004) and in northern Africa (Lamb et al. 1995). It also coincides with the aridity crises of 4,200 years ago in West Asia associated with the collapse of the Egyptian Old Kingdom and the Akkadian Empire (Cullen et al. 2000), and the relatively dry period between 2550 and 1850 BC (4500–3800 cal BP) that occurred globally (Mayewski et al. 2004).

After 1850 BC, the decline of pennate species and the proliferation of *C. cyclopuncta*, which became dominant by 1490 BP, reflect lake level recovery, in

**Table 1** Overview of sediment results (diatom, pollen, algae, macrophyte remains) and resultant climate and environmental inferences. Summary data and inferences are plotted along with corresponding regional climate features and historic periods. Environmental and climatic inferences are made using diatoms, pollen (Rull et al. 2010), sedimentological records (Corella et al. 2010) and historical information (Còts 2005; Marugan and Oliver 2005). *MCO* medieval climatic optimum, *LIA* little ice age

| Diatom zones | Litho-stratigraphic units | Pollen zones | Aquatic macrophytes | Algae | Inferred lake level | Environmental and climatic inferences | Regional climatic features | Historic periods |
|---|---|---|---|---|---|---|---|---|
| **V** Dominance of *C. cyclopuncta* (AD 1300-0) | **I** Low clastic input | **M6** Conifer forest. Hemp decline, olive | *Cyperaceae* | *Botryococcus* | Level recovery | Decreased erosion, oligotrophy, depopulation, likely warming | Present day warming | Hemp cult. decline (AD 1860) |
| | **II** High clastic input | **M5** Forest patches. Hemp, olive | *Typha/Sparganium* | | | Vegetation shift, agrarian expansion, erosion | LIA | Modern Period |
| | **III** Low clastic input | **M4** Conifer/oak forest. Shrublands. Olive | *Cyperaceae Cladium* | | | Dry and cool phase, short depopulation | Sporer min. (~AD 1460-1550) | |
| | **IV** High clastic input | **M3** Forest patches, scrubs.Declining pastures/crops, hemp retting | | | | | LIA | Late Middle Age (~AD 1300-1450) |
| **IV** Scarce or lacking diatoms (AD 710-1300) | | **M2** Forest patches. Pastures/herb, crops. Fire | *Cyperaceae* | *Botryococcus Pseudoschizaea Tetraedron* | Lower level | Overpopulation, eutrophication of the lake. Warm and dry climate, enhanced erosion | MCO (~AD 1100-1350) warming | High Middle Ages (~AD 1000-1300) |
| | | **M1** Conifer forest. Meadows, pastures, herbaceous crops | | | | | Arid period (~AD 900-1100) | Early Middle Ages (~AD 700-1000) |
| **III** Dominance of *C. comta* (605 BC - AD 710) | **V** Low clastic input | | | | Level recovery | Livestock and crops development lead to erosion and nutrient enrichment | | Visigoth period (~AD 420-710) |
| | | | | | Lower level | | Humid period in the Mediterranean | Iberian-Roman age (~70 BC - AD 420) |
| | | | | | Maintained levels + shallow phases | | Floods reduction (~400-50 BC) | Iron age (until ~AD 400) |
| **II** Dominance of *C. cyclopuncta* (2420-605 BC) | | | | | Lower level | Non-significant local impacts | | |
| | | | | | Level recovery | | | |
| | **VI** Dissolution of endogenic calcite, hypolimnion acidic conditions | | | | Littoral environment | Climatic instability | Aridity crises (~2550-1850 BC) | Chalcolithic Period + bronze age (until ~1250 BC) |
| **I** Dominance of *C. comta* (3390-2420 BC) | | | | | Maintained levels with shallow phases | Nutrient input from forest clearings fires | | |
| | | | | | | | African humid period (until ~3550 BC) | Neolithic (~4000-3000 BC) |

agreement with the enhanced basin runoff and sediment input identified by Corella et al. (2010) (1850–400 BC; subunit Vc). Valve influx reaches the highest values around 950 BC, when the lake was highly productive. This *C. cyclopuncta*—rich period was interrupted by Fragilariales, probably indicating phases of climatic instability. This period (1850–900 BC) is synchronous with a humid phase documented at other sites in the Mediterranean area (Martín-Puertas et al. 2008; Sadori et al. 2004). At the top of the zone, *C. cyclopuncta* completely disappears along with an increase in small Fragilariales, associated with higher alkalinity and conductivity. Together with a decline of valve influx (900–750 BC), this points to another lake level decrease.

Nutrient concentrations in sediment, especially TP, are generally lower than in the previous zone (the Neolithic Age) and might be a result of decreased runoff during drier periods. Changes in the redox conditions at the bottom of the lake could also help explain lower P release. Especially in meromictic lakes, more TP can be released from the sediment under anoxic conditions (Nürnberg 1994; Burley et al. 2001; Schmidt et al. 2004), thus fertilizing the water column even when external P sources decrease (Welch and Cooke 1995; Petticrew and Arocena 2001). In some cases, P input from the sediment can be even higher than external loading (Penn et al. 2000). The abundance of pyrite (FeS) (Corella et al. 2010) in this interval is also indicative of strong anoxic conditions, under which Fe forms pyrite and is unable to bind phosphorus, thereby favoring its release from the sediment.

This interval includes the Chalcolithic Period and the Bronze Age (750–150 BC, 2700–2050 cal BP) when copper and bronze metallurgy demanded more wood for ovens to melt metals, and agriculture became a common practice. These cultural changes could have triggered deforestation and erosion of bare soils (Còts 2005; Bosch and Santacana 2009), but it is likely that local impacts were still not significant.

### 605 BC–AD 710; 2555–1240 cal BP (Diatom zone III); Iron Age, Iberian-Roman Age, Visigoth period

At the base of the zone (605–170 BC), the return of *C. comta* and the disappearance of *C. cyclopuncta* suggest a return to limnological conditions similar to zone I. Between 170 BC and AD 125, a new decrease of lake level is indicated by a decline of *C. comta* in favour of pennate species and the presence of *C. pseudostelligera* and *G. lateripunctatum,* which can tolerate ion-rich environments (van Dam et al. 1994). Deposition of littoral, organic-rich facies with abundant gastropod remains also points to lower lake levels (400 BC to AD 40). At a regional scale, this period coincides with a reduction in river flood frequency in the IP (Macklin et al. 2006) between 400 and 50 BC, and lower levels in Zoñar Lake between 150 BC and AD 50 (Martín-Puertas et al. 2008).

Subsequent recovery of *C. comta* and an increase in valve influx (AD 125–565) indicate a clear return to planktonic conditions and higher lake levels during the end of the Roman epoch, a documented humid period in the Mediterranean area (Reale and Dirmeyer 2000). This period coincides with the formation of abundant calcite laminae indicative of high productivity in the epilimnion (Corella et al. 2010), with seasonal *Cyclotella* peaks leading to calcite whitings in the lake (Fig. 2). Comparable increases in lake levels were also observed in records from nearby Lake Estanya in the Pre-Pyrenees (Morellón et al. 2008), as well as in Andalucia (Lake Zoñar, Martín Puertas et al. 2008). A second decrease in lake level is observed at the top of the zone (AD 710), coinciding with an increase of *M. smithii*, *G. lateripunctatum*, *S. pinnata* and *P. brevistriata*. The periods around 600 BC and AD 700 were also unstable in the Alps, but were wet, as reflected by mid-European lake-level fluctuations (Magny 2004; Schmidt et al. 2004).

In the Pallars region, iron metallurgy was not known until about 450 BC, but even then, human pressure in the region was likely as restricted as during the Bronze Age (Còts 2005). Significant cultural transformations occurred in the IP during the Iberian-Roman Period, but no Roman settlements existed around the lake. As in other mountain areas, forests and iron mines were exploited to meet Roman public and domestic needs (Còts 2005). After the decline of the Roman Empire, important changes in resource exploitation took place, with extensive livestock development and expansion of crops in the valleys. Locals undoubtedly intensified landscape transformation, leading to erosion and nutrient enrichment of water bodies initiated in previous epochs (Còts 2005; Bosch and Santacana 2009).

AD 710–1300; 1240–650 cal BP
(Diatom zone IV); upper middle age

This interval is synchronous with the Medieval Climate Anomaly (MCA), an enduring warm and dry phase in the Northern Hemisphere (Seager et al. 2007). The scarcity or even lack of diatoms in this zone suggests very unfavourable conditions for diatom preservation. Warming and lower lake levels alone seem insufficient to explain the near absence of diatoms in this sequence. Concentration of carbonates due to lower lake levels and the inflow of carbonate-charged groundwater may have raised pH values in the monimolimnion, interstitial waters and at the sediment–water interface, high pH being the single most important factor affecting diatom dissolution (Ryves et al. 2001). Additionally, hemp (*Cannabis sativa*) was grown around Lake Montcortès since AD 800 (Rull et al. 2010). This practice is known to alter water composition and impact algae (de Bonneville 1994; van der Werf 2004). It may also accelerate decay of frustules that contain a pectin membrane in the inner part (Round et al. 1990).

Finally, the scarcity of diatoms could be a consequence of the dominance of clastic material during this interval, caused by an increase in sediment delivery to the lake. Sample resolution may be poor due to the high frequency of thick turbidite layers in the record. Lower TIC, TOC and TN values are due to the dilution effect caused by the presence of these cm-thick detrital layers.

Littoral vegetation was dominated by *Cyperaceae* (others) during the whole interval represented by this zone, but a significant change occurred around AD 1170 (780 cal BP) with the appearance of *Cladium*, which established as an important component of the littoral vegetation until the end of the zone. This coincided with an increase in fire incidence and other human activities, possibly related to of drier climates (Rull et al. 2010). On the other hand, the population in montane areas increased as people retreated from the northward advance of Muslims (AD 711–800), and these increased numbers could have been responsible for enhanced erosion and runoff (Marugan and Oliver 2005). Dominance of *Botryococcus* is typical in lakes of diverse depths and water quality, hence its palaeolimnological interpretation is not straightforward. Two pronounced peaks of *Tetrahedron* occur at about AD 900 and 1200, respectively. Because they coincide with two maxima in carbon concentration, they could indicate sudden and ephemeral eutrophication events due to increases in shifting agriculture (Rull et al. 2010). Such shifting agriculture produces large impacts on landscape and a sudden increase in nutrient input to the water bodies. However, due to the itinerant nature of this practice, impacts are local and temporary. Increases in sediment TP seem to be related to higher sediment delivery to the lake from the watershed, caused by higher human impact. In the Mediterranean region, *Pseudoschizaea* increases have been associated with low lake levels and dry climates (Carrión et al. 2004, 2007), so its fluctuations may indicate oscillations in these environmental parameters. In Lake Montcortès, Rull et al. (2010) found a coeval warming between AD 1100 and 1350 (850 and 600 cal BP), inferred from an upward displacement ($\sim$200 m) of a thermophilous plant association. Frequent oscillations in both macrophytes and algae (Figs. 4 and 5) indicate that the lake fluctuated around low levels. Other lakes of the IP displayed low-water phases between the tenth and twelfth centuries (Morellón et al. 2009a; Valero-Garcés 2008). Likewise, a concurrent aridity increase in lakes of central Italy (Dragoni 1998) and northern Africa (Lamb et al. 1995) has been reported. The abundance of detrital layers has also been interpreted in terms of the synergistic effects of warmer and drier climate and greater human pressure (Rull et al. 2010; Corella et al. 2010).

650 cal BP to Present, AD 1300 to Present
(Diatom zone V); lower middle age, modern and postmodern periods

This interval begins with a recovery of lake level, indicated by the rapid increase of valve influx and of *C. cyclopuncta* abundance. The littoral vegetation is the same as in the former zone, that is, *Cyperaceae* is dominant and *Cladium* is an important component. The beginning of zone V corresponds with the onset of the Little Ice Age (LIA) in the IP (Moreno et al. 2008; Benito et al. 2003). In the IP, the LIA was characterized by a variable, cooler and wetter climate (Pla and Catalan 2005; Chueca Cía et al. 2005), leading to higher lake levels in nearby Lake Estanya (Morellón et al. 2008). In Montcortès Lake, valve influx decline, accompanied by a slight decrease in the abundance of *C. cyclopuncta*, and a rise in some

pennate species (remaining taxa, Fig. 2), was observed between about AD 1400 and 1460 and may indicate that a short-lived drier and cooler phase occurred within the LIA. A decrease in the calcite thickness, and thus in productivity, is observed in the varves. In nearby Lake Estanya, some changes about AD 1440 suggest colder conditions coincident with the Spörer minimum in solar irradiance (Morellón et al. 2009a). Around AD 1500, this situation reversed. TP declines, coinciding with a severe socioeconomic crisis that occurred between AD 1350 and 1487. In the Pallars region, one-third of the population nuclei disappeared, with the consequent abandonment of their respective lands, crops, pastures, forests and natural resources, due to wars and the devastating "black death" epidemic that occurred in AD 1348. Recovery from the Early Medieval crisis, in terms of number of houses, was relatively rapid, but population numbers remained below the levels attained during the eleventh to thirteenth centuries (Marugan and Oliver 2005).

Modern times (fifteenth to eighteenth centuries) began with changes in the ownership of natural resources. Pastures underwent significant expansion linked to technological improvements for water transport and irrigation. During pre-industrial time, i.e. the end of the eighteenth century to AD 1870, the isolation of the Pallars region determined the diversification of the subsistence economy. A major vegetation change occured in the littoral plant communities. *Cladium* disappeared from the littoral assemblage around AD 1660, following an increase in sedimentary TP and was replaced by *Typha/Sparganium*, which was co-dominant with other *Cyperaceae* from that point. The replacement of *Cladium* by *Typha* in littoral communities is typical in situations of sustained increases in nutrient supply (N and P) to lakes. Indeed, *Typha* seems to have increased photosynthesis more efficiently and accumulated more biomass, thus out-competing *Cladium*. This phenomenon was first noticed in modern communities of North America (Chiang et al. 2000), but it has also been documented in the Mediterranean region (Alvarez-Cobelas and Cirujano 2007). The vegetation shift occurs at the same time as agrarian expansion after the LIA, manifested in the absolute maximum of *Cannabis* cultivation and likely retting in both Lakes Montcortès and Estanya (Riera et al. 2006; Rull et al. 2010).

Higher clastic input and intense soil erosion in the catchment during this period coincided with a phase of maximum prosperity of the naval industry, which needed hemp fiber in large quantities for ropes and sails (Andreu 1981; Delgado 1994). Diatoms were present only in traces, indicating the return of very unfavourable preservation conditions and associated with the deposition of clastic unit II. Increased sediment delivery to the lake during the nineteenth century (unit II) reflects a period of intense human transformation of the watershed. In fact, diatom influx remained low until about AD 1860, when hemp cultivation sharply declined (Rull et al. 2010). Among the algae, absence of *Pseudoschizaea* and *Tetrahedron* suggests that the external anthropogenic inputs to the lake were different from former periods, with respect to erosion and eutrophication (AD 710–1300). Charcoal increased only slightly, indicating that fire was not important in forest clearance for cultivation, and that wood was probably used for building, lighting, industry, and other purposes (Rull et al. 2010).

The last interval represents the twentieth century to present, and encompasses the end of the LIA and the subsequent warming trend. Diatom flux increases moderately and *C. cyclopuncta* persists until recent times. The appearance of *C. ocellata*, which is a mesotrophic to oligotrophic species, may reflect a trend toward lower nutrient status of the lake. Today the lake is oligotrophic. TOC and TIC values increase as varved sediments dominate again and clastic sediment delivery to the lake decreases, reflecting the depopulation of the region, first as a consequence of the general agricultural crisis, but later due to massive emigration from rural to urban areas. Today, the main economic activities of the Pallars region are tourism and related services (Farràs 2005), all of which have relatively little impact on Lake Montcortès. Table 1 displays an overview of results from the diatom record and other algae and pollen analysis with regard to human cultures and regional environmental and climatic inferences for the period studied.

## Conclusions

The main pattern of diatom variation in the sediment stratigraphy from Lake Montcortès over the last 6,000 years is alternation between *C. comta* and

*C. cyclopuncta. C. comta* dominates over *C. cyclopuncta* during periods of higher trophic state. Once one of the *Cyclotella* species has become dominant, it remains so for millennia. Small Fragilariales are eurytopic and often associated with unstable environments. The main species found tolerate high conductivity and pH values. Therefore, proliferation of those Fragilariales in Lake Montcortès, along with decreases in valve influx and low *Cyclotella* abundances, are interpreted to reflect low and fluctuating water level. The diatom record indicates periods of increased productivity and fluctuating lake levels prior to 2300 BC (Neolithic period). The first shift from *C. comta* to *C.cyclopuncta* occurred during the Chalcolithic period and is interpreted as a re-oligotrophication of the lake during an intense arid phase (2360–1900 BC). Afterwards, lake level recovery took place (1850–900 BC), followed by another dry period (900–750 BC). During the Bronze Age and the Neolithic period, local human impacts were negligible, thus phosphorus influx to the sediment and availability in the epilimnion were mainly controlled by climate. The recovery of *C. comta* (605 BC–AD 710) indicates a relative increase in lake level, with its maximum during the Iberian-Roman epoch, although peaks in Fragilariaceae suggest unstable, drier environmental conditions at the beginning and end of this period. During the Medieval Ages (AD 710–1300), vegetation changes and increased clastic deposition reflect drier climate, decreasing lake levels and increased human pressure, synchronous with the MCA. Prevailing alkaline conditions could be responsible for diatom dissolution. This period was followed by recovery of *C. cyclopuncta*, suggesting a relative increase in lake level during the LIA and more oligotrophic conditions, probably associated with the depopulation of the Pallars due to the Early Medieval crisis. During pre-industrial times (fifteenth–eighteenth centuries), the replacement of *Cladium* by *Typha* in littoral communities points to increased nutrient supply, which coincides with the agrarian expansion of the modern age. During the twentieth century, the diatom record reflects an impoverishment of the lake's trophic state, reflecting the severe depopulation of the region.

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